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PERFORMANCE OF A SMALL SOLAR-POWERED HYBRID MEMBRANE SYSTEM FOR REMOTE COMMUNITIES UNDER VARYING FEEDWATER SALINITIES

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SUMMARY

An estimated 1 billion people are living both without access to clean drinking water or electricity. The small photovoltaic (PV)-powered hybrid membrane system described here is designed to address the plight of some of these people. PV and membrane technologies are chosen due to suitability for operation in remote and often harsh conditions. An ultrafiltration (UF) pre-treatment is included to remove bacteria and most pathogens, while a reverse osmosis (RO) or nanofiltration (NF) membrane desalinates the brackish feedwater. Several parameters were examined in order to optimise the system performance, including i) feed salt concentration, ii) operating pressure, iii) system recovery, iv) specific energy consumption (SEC, kWh/m^3), and v) salt retention. In addition, experiments were performed over a whole day to determine system performance under varying levels of solar radiation. The minimum SEC (relatively high due to the current single-pass mode of operation) varies from 5.5 kWh/m^3 at a feed concentration of 1 g/L salt to 26 kWh/m^3 at a feed concentration of 7.5 g/L salt, which is the upper limit of the system in terms of salt concentration.

Keywords: Remote community, developing country, desalination, membrane filtration, solar energy, photovoltaics.

1 INTRODUCTION

A United Nations Development (UNDP) report has identified that there are 1.3 billion people who do not have access to adequate quality drinking water (UNDP 1998), while World Health Organisation (WHO) statistics indicate that 80% of all diseases in developing countries are water-born (WHO 1993). Annually, 2 billion cases of diarrhoea are registered, and more than 5 million deaths are associated with the consumption of poor quality drinking water. The majority of these deaths are children (WHO 1993). The UNDP report also found that about 2 billion people are living without electricity (UNDP 1998). Furthermore, it has been estimated that the overlap between the groups living without electricity or clean water amounts to 1 billion, or 17% of the world's population (Parodi *et al.* 2000). This fact, together with the aim of providing sustainable technology, invites the initiative to combine water treatment with renewable energy. This paper investigates a treatment solution that provides drinking water to such remote communities and developing countries using such technology. In particular, photovoltaic (PV) power would appear to be idea, given that many regions that possess a limited and/or poor quality drinking water also exhibit high levels of solar radiation.

2 EXISTING SOLAR MEMBRANE SYSTEMS

It is already widely known that PV-powered water pumping systems are extremely reliable, and are able to provide water in remote areas for the lowest costs (Bröker *et al.* 1998, Thomas 2001). Desalination can be accomplished through one of two processes: phase change or membrane separation. Simple distillation, multistage flash, freeze separation all involve a phase change of the feed water (either to vapour or solid), whereas reverse osmosis (RO) and electrodialysis rely on the properties of plastic membranes. The specific energy consumption (SEC) – the energy required to produce a unit of clean water – of a phase change process is proportional to the amount of water produced, whereas the SEC for a membrane separation process are proportional to the salinity of the feed water (Block and Melody, 1989). A comparison of typical SEC (kWh/m^3) for solar-powered desalination technologies is provided in Table 1. The advantages of the membrane processes are that they are modular technology, easy to install, compact in size, simple to operate (Block and Melody, 1989), and can operate mostly free of chemicals.

Table 1 Typical energy requirements for solar-driven desalination technologies (adapted from Block and Melody, 1989). The minimum value that is theoretically achievable is 0.8 kWh/m^3.

Desalination Technology	*Energy Sink*	*Applicable Solar Energy Source*	*SEC (kWh/m^3)*
Solar still	Evaporation and condensation of water	Direct solar thermal	639
Multistage Flash Distillation	Boiling and condensing with heat recovery, and pumping	Solar thermal (troughs, dishes or evacuated tubes), solar electric	64
Freeze Separation	Freezing and melting of ice crystals	Photovoltaic or absorption for refrigeration; solar thermal for melting	97
Electrodialysis	Passing electric current through membrane stack, and pumping	Photovoltaic	11
Reverse Osmosis	High pressure pumping	Photovoltaic	4

In addition, Table 1 shows that RO treatment of seawater has the lowest SEC of all desalination technologies, and that the energy is almost entirely consumed by high-pressure pumps. As the SEC is dependent on the feedwater salinity, a significantly lower SEC can be expected for membrane filtration of brackish water. Many of the advantages of membrane processes are also shared by PV, making the coupling of membrane technology to a PV-powered system in a remote location an ideal match. However, membrane technology cannot match the almost zero level of maintenance required for PV, and the membranes have a relatively short (about 5 yr) lifespan (Block and Melody, 1989). Many examples of photovoltaic-powered reverse osmosis (PV-RO) treatment systems can be found in the literature. The majority of PV-RO systems have been designed to operate at high pressures (> 40 bar) in order to desalinate seawater (typical salinity 35 g/L). An overview of such systems and their applications is shown in Table 2.

Table 2 Overview of existing PV-RO units (TDS: total dissolved solids; ERD: Energy recovery device).

Location	*TDS Conc. (g/L)*	$P_{operate}$ *(bar)*	*Salt Rejection (%)*	*Recovery (%)*	*Clean Water (m^3/d)*	*PV Array (kW$_p$)*	*ERD*	*Battery*	*SEC (kWh/m^3)*	*Reference*
Portugal	2 – 5 mS/cm	4	90	2	0.02	0.15	No	No	25.6	Joyce *et al.* 2001
Australia	5	–	–	16 or 25	0.4	0.12	Yes	No	–	Mathew *et al.* 1999, 2000
Canada	33	34 – 55	97 – 99	14	0.85	0.48	Yes	No	4.0	Keefer *et al.* 1985
Australia	–	–	88	–	0.4 – 1.0	1.2	No	Yes	4.0 – 5.8	Crutcher *et al.* 1983; Block & Melody 1989
UK	40	40 – 60	–	–	3 †	2.4 †	Yes	No	3.5 †	Thomson *et al.* 2002a, 2002b
Mexico	Brackish	40	–	–	0.7 – 1.4	2.5	No	Yes	4.0 – 6.9	Petersen *et al.* 1979, 1981
Oman	1	12	96.6	65 – 70	5	3.25	No	Yes	2.3	Al Sulaeimani & Nair (2000)
Israel	4	14 – 16	98	50	3	3.5 *	No	Yes	–	Weiner *et al.* 2001
Spain	35	45 – 70	>98.5	–	> 0.8	4.8 *	No	Yes	15 – 16	Herold *et al.* 1998, 2001

* System is equipped with inverter(s) and AC pump(s). † Simulated results.

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3 SYSTEM DESIGN

The system was designed for a small community as a central source for potable water that would be collected from the system directly. The system recovery would be low (about 10%) to treat a small amount of water for drinking and cooking purposes, while the remainder of the water would be microbiologically safe and of sufficient quality for personal hygiene or cleaning purposes in most locations. This was achieved with an ultrafiltration (UF) pre-treatment which removes bacteria and most pathogens, in conjunction with the RO or nanofiltration (NF) membrane. The system is illustrated in Figure 1 with a schematic and in Figure 2 with a picture.

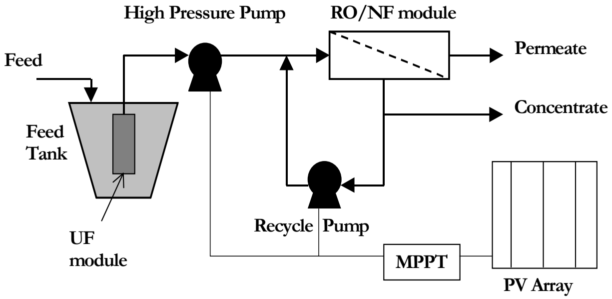

Figure 1 Schematic diagram of the PV-powered hybrid membrane system (MPPT: maximum power point tracker).

The pre-treated water is sucked through the UF membrane with a pressure of up to -0.5 bar and then pressurised to 5 – 7 bar for treatment with RO or NF membrane. The clean water or permeate is stored in a water tank to avoid the usage of batteries. Inverters, which incur energy losses and are prone to failure, were also avoided. While provision for a recycle pump is made in the system to allow an increased recovery (percentage of clean water produced from feed water), this pump was not used in this trial and the system was operated in single pass mode.

The UF not only cleans the water, UF is also an effective pre-treatment process that removes particulate and colloidal matter that may cause the NF/RO membranes to foul prematurely. While most systems use cartridge filters as pre-treatment, such filters cannot adequately remove smaller particles and bacteria (which may cause biofouling) and hence the systems will require more frequent cleaning.

Figure 2 Picture of the system with enlargement of feed tank and ultrafiltration membranes.

4 EXPERIMENTAL METHODS

The system consisted of a ZeeWeed 10 module (Zenon Environmental, Canada), directly immersed in the feed tank. A low pressure RO membrane module was selected for the desalination stage (FilmTec TW30-2521). It is characterised by a high sodium chloride retention and a relatively low operating pressure (4-10bar). The positive displacement pump (Dankoff Solar Slowpump Model 1322) was selected. The rotary vane pump has a maximum operating pressure of 13.2 bar at a flowrate of 89 L/h. Four BP Solar laser-grooved, buried-grid silicon solar cells were chosen due to their high efficiency (>15.5%), with each panel provided a maximum power output of 85 Watt. The panels were connected in parallel and a MPPT (Dankoff Solar Model DL-8A) used to optimise power output for the pump.

All experiments were carried out using the same system setup with regard to location, alignment of the solar panels, and system configuration. The solar panels were tilted at an angle of 25˚ to the horizontal plane and were facing northwards, without being moved during the experiments. The 200L feed tank was filled with tap water, and table salt was added to adjust the different salt concentrations. Before the first measurement of the day, the system was run for at least 15 minutes to stabilize the performance of the membrane and to bleed air trapped in the system. The operating pressure of the RO/NF module was regulated by adjusting the needle valve of the concentrate stream. Both the permeate and the concentrate were recycled back into the feed tank to maintain a stable feed concentration, and the sampled water was put back in the feed tank after it was analyzed for conductivity, temperature and pH.

The permeate and concentrate flow rates were determined using a plastic measuring cylinder (volume: 1000 mL) and a stopwatch. The feed flow rate was assumed to be the sum of permeate and concentrate flow rate (single pass configuration). The samples were analyzed using a universal meter (WTW Multi-line P4), which measures conductivity, temperature and pH.

5 SYSTEM OPTIMISATION RESULTS & DISCUSSION

To optimise the system, a number of parameters were examined (1) feed salt concentration, (2) operating pressure, (3) system recovery, (4) energy requirement per unit of clean water, and (5) salt retention. Furthermore, test runs were performed over a whole day to determine system performance under varying levels of solar radiation. Several key parameters of the system were measured during the experiments, such as permeate flow, module recovery, operating pressure, salt rejection, and power consumption. These are important characteristics of the system, and they can be helpful for further optimization of the system design and operating conditions.

Effect of Feed Salinity on Flux and Recovery

The aim of the trials was to determine the limitations of the system with regard to feed water salinity. As the salt concentration increases the osmotic pressure of the feed increases which reduces the effective transmembrane pressure. Concentration polarisation, which is the accumulation of salt retained by the membrane, further enhances this effect and is stronger the higher the retention of salt by the membrane. This effect is reflected by the results in Figure 3; permeate flux increases with increasing pressure and is highest for the lowest salt concentration. For high transmembrane pressures permeate flux decreases for two reasons; firstly, the salt concentration is increased and secondly, the flow has to be restricted with a valve to achieve the higher pressure and hence recovery increases leading to additional increases in salt concentration. In addition the pump performance decreases at higher pressure. This effect is further emphasised in Figure 4 at 1 g/L salt showing the variation of flow rates and the increase in recovery with increasing pressure and Figure 5 which shows the variation of recovery for all salt concentrations as well as the line for optimum permeate flux.

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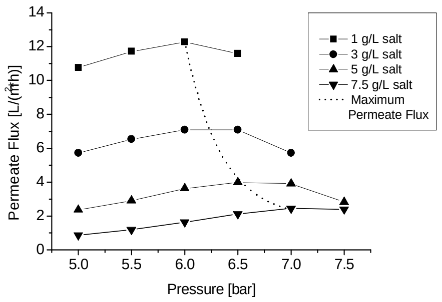

Figure 3 Permeate flux as a function of transmembrane pressure for varying feed salt concentrations.

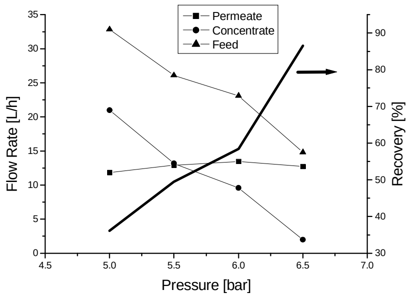

Figure 4 Variation of system flow rates and recovery with transmembrane pressure (1 g/L feed salt concentration).

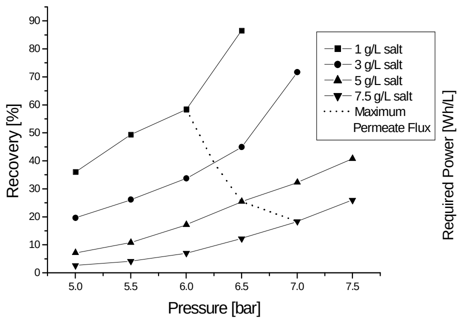

Figure 5 Water recovery as a function of transmembrane pressure for varying feed salt concentrations.

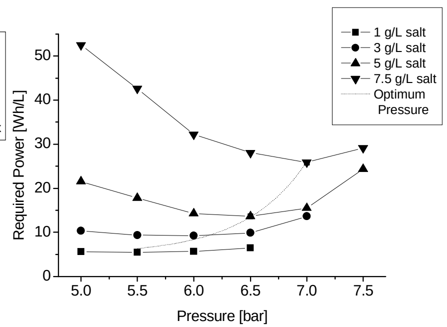

Figure 6 SEC (Wh per L of treated water) as a function of transmembrane pressure and salt concentration.

Specific Energy Consumption (SEC)

The SEC indicates the energy efficiency of the system, which is an important design attribute. To optimise the energy efficiency, the required energy (Wh) per litre of product water should be minimised by either varying the operating conditions (e.g. pressure) or the system configuration (e.g. pump, option of energy recovery). A low SEC translates to lower system costs, as the solar panels contribute a major part to the capital costs.

Different parameters are strongly interlinked and with solar power it is difficult (if not impossible) to perform experiments in a way that keeps all parameters except the one to be examined constant. The power requirements depend on recovery, pressure and hence salt concentration. This is shown in Figure 6 where an optimum operating pressure can be found for each salt concentration. The optimum stems from the fact that initially the productivity of the unit increases with increasing transmembrane pressure until recovery gets too high and salt concentrations affect permeate flux. This optimum value is strongly dependent on pump performance and will invariably be different for each system. The minimum of required energy per litre of permeate varies from 5.5 kWh/m^3 at a feed concentration of 1 g/L salt to 26 kWh/m^3 at a feed concentration of 7.5 g/L salt. The values are higher than those shown in Table 1 due to the single pass approach and the very small system.

Figure 7 illustrates how permeate flow, power consumption and pressure influence the required energy per litre of product water. The SEC decreases until permeate flow drops due to pump and salinity limitations. Ideally, the feed flow rate should be rather constant to maintain a high cross-flow velocity and prevent excessive concentration polarisation caused by high recoveries. A constant feed flow rate is supposed to increase the achievable maximum permeate flux at high operating pressure and hence shift the optimum pressure to higher values.

Impact of Operating Conditions on Salt Retention

One of the main research objectives of this project is to determine the operating window for a solar membrane system. This is of relevance as the energy source is not constant and hence operating pressure, flows and recovery will naturally vary over the course of a day. In many systems those variations are compensated for with the use of a battery. As discussed above the use of a battery is not desirable due to the limited life span of batteries and other issues (Richards and Schäfer 2003). The project in general is concerned not only with desalination, but also the removal of trace contaminants and their retention needs to be reliable. In this paper, water quality is represented by salt removal.

The salt retention was calculated using the measured conductivity values of the permeate and feed stream, because conductivity is directly proportional to salt concentration (assuming that the composition of the salt is not varied in the process). Hence, the retention (R) is

$$R = (1 - \frac{Conductivity_{permeate}}{Conductivity_{feed}}) * 100\%$$

The results of salt retention as a function of transmembrane pressure and feed concentration are shown in Figure 8. The retention decreases with increasing pressure, which was unexpected, as the salt retention of RO membranes normally increases with rising transmembrane pressure. A possible explanation is the increased concentration polarisation effect due to high recovery and low cross-flow velocity. This leads to a high concentration of rejected ions near the membrane surface, thus developing a high concentration gradient from the concentrate side to the permeate side of the membrane. This gradient may cause extensive diffusion of ions across the membrane into the permeate stream, resulting in a lower salt retention of the membrane module.

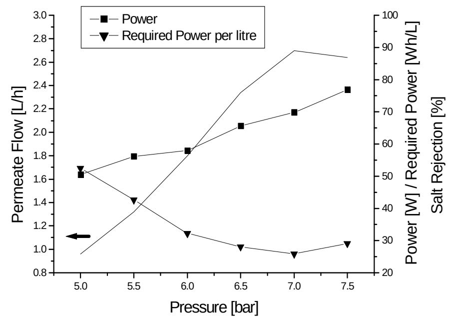

Figure 7 Variation of permeate flow, power consumption and SEC as a function of transmembrane pressure.

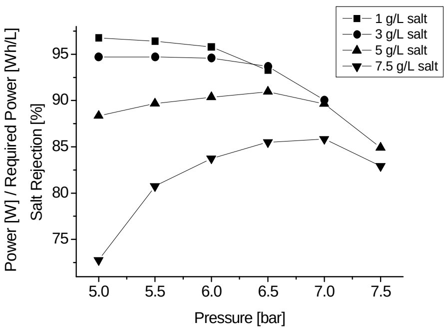

Figure 8 Salt retention as a function of transmembrane pressure for varying salt concentrations.

Performance in All-day Test Runs

The performance of the system was tested over a whole day to determine the minimum or threshold amount of solar radiation that is necessary to operate the unit. The impact of temporarily varying solar radiation levels (e. g. clouds) on the process stability of the system was also examined. Figure 9 shows the variation of permeate flow and solar radiation over a day. The permeate flow is relatively constant throughout the day, although the solar radiation varies significantly due to partly cloudy weather conditions at the beginning of the day. At the end of the day the operation of the maximum power point tracker (MPPT) shows a nice impact in that the performance remains stable for a long period until the water production ceases abruptly.

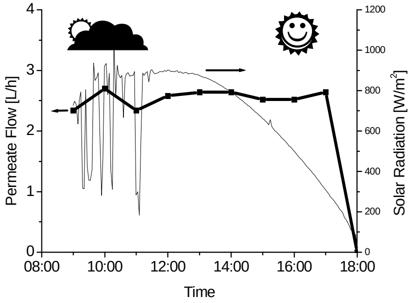

Figure 9 Permeate Flow and Solar Radiation vs Time of day (Feed concentration: 5 g/L, pressure: 5 bar, 2 solar panels)

Altogether, the results of the all-day test runs show that the unit is able to produce a constant permeate flow even under partly cloudy conditions. The possible operating time per day should depend on the span of time in which the threshold level of solar radiation is reached. The system operates at maximum flow with only 2 solar panels. This was expected as each solar panel has a maximum power output of 85 W, which adds to 170 W maximum output. The pump draws a maximum of 100 W at an operating pressure of 8 bar, leaving sufficient room to compensate for the decreased power in the sun in early morning and late afternoon, and also during cloudy periods.

6 CONCLUSIONS

The PV-powered hybrid membrane treatment system described here has shown excellent performance over a wide operating range. As the feed water salinity was varied from 1 g/L to 7.5 g/L in the brackish water range, the maximum in permeate flux increased with rising pressure and was highest for the lowest salt concentration. The recovery also increased with increasing pressure, and the optimum permeate flow rates were found.

Achieving a low SEC is important in order to reduce the initial capital cost of the PV-RO system. An optimum operating pressure was found for each salt concentration, and the SEC varied from 5.5 kWh/m^3 at a feed concentration of 1 g/L salt to 26 kWh/m^3 at a feed concentration of 7.5 g/L salt. The SEC decreases until permeate flow drops due to pump and salinity limitations. The values are somewhat higher other systems found in the literature due to the single pass approach used.

The result of salt retention decreasing with increasing pressure was unexpected, as the salt retention of RO membranes normally increases with rising transmembrane pressure. A possible explanation is the increased concentration polarisation effect due to high recovery and low cross-flow velocity combined with a pump performance loss at high pressure. This results in a high concentration of rejected ions near the membrane surface, thus developing a high concentration gradient from the concentrate side to the permeate side of the membrane. This gradient may cause extensive diffusion of ions across the membrane into the permeate stream, resulting in a lower salt retention of the membrane module.

Finally, the results of the all-day testing indicated that the PV-RO unit is able to produce a constant permeate flow even under quite cloudy conditions. Further studies will be performed on the optimisation strategies to make the best use of available power during the day, while maintaining the desired water quality.

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BIBLIOGRAPHY

Al Suleimani Z. and Nair V.R. (2000), *Desalination by solar-powered reverse osmosis in a remote area of the Sultanate of Oman*, Applied Energy 65, pp. 367-380.

Block D.L. and Melody I.I. (1989), *Assessment of Solar Desalination Processess*, Proc. Solar '89, American Solar Energy Society, pp. 62-71.

Block D.L. and Melody I.I. (1989), *Assessment of Solar Desalination Processess*, Proc. Solar '89, American Solar Energy Society, pp. 62-71.

Bröker C., Carvalho P.C.M., Menne K., Ortjohann E., Temme L. and Voß J. (1997), *Design of a photovoltaically operated reverse osmosis plant in off-grid operation for desalination of brackish water*, Proc. 26th IEEE Photovoltaics Specialists Conference, pp. 1329-1332.

Crutcher J.L. (1983), *Photovoltaic-powered desalination*, Photovoltaics, The Solar Electric Magazine 1(5), pp. 28-31.

Herold D., Horstmann V., Neskakis A., Plettner-Marliani J., Piernavieja G. and Calero R. (1998) *Small scale photovoltaic desalination for rural water supply – demonstration plant in Gran Canaria*, Renewable Energy 14(1-4), pp. 293-298.

Herold D. and Neskakis A. (2001) A *small scale PV-driven reverse osmosis desalination plant on the island of Gran Canaria*, Desalination 137, pp. 285-292.

Joyce A., Loureiro D. , Rodrigues C. , Castro S. (2001). *Small reverse osmosis units using PV systems for water purification in rural places.* Desalination 137, pp. 39-44.

Keefer B.G., Hembree R.D. and Schrack F.C. (1985), *Optimized matching of solar photovoltaic power with reverse osmosis desalination*, Desalination 54, pp. 89-103.

Mathew K., Dallas S., Ho G.E., Anda M. (1999) *A solar-powered village water supply system from brackish water*, World Renewable Energy Conference VI, pp2061-2064.

Mathew K., Dallas S., Ho G.E., Anda M. (2000) *Commercialisation of an innovative solar-powered village potable water supply*, Australian & NZ Solar Energy Society Conference: Solar 99.

Parodi O., Preiser K. and Schweizer-Ries P. (2000), *Clean water with clean energy: a huge market for PV – but not yet explored*, Proc. 16th European Photovoltaic Solar Energy Conf., Glasgow, U.K., May 2000.

Petersen G., Fries S., Mohn J. and Müller A. (1979), *Wind and solar powered reverse osmosis desalination units – Description of two demonstration projects*, Desalination 31, pp. 501-509.

Petersen G., Fries S., Mohn J. and Müller A. (1981), *Wind and solar powered reverse osmosis desalination units – Design, start up, operating experience*, Desalination 39, pp. 125-135.

Richards B.S., Schäfer A.I. (2003), *Photovoltaic-powered desalination system for remote Australian communities*, Renewable Energy 28, pp. 2013–2022.

Thomas M.G. (2001), *Water pumping: The Solar Alternative*, Sandia National Lab,, Albuquerque, NM, USA.

Thomson M., Infield D. (2002a). *A photovoltaic-powered seawater reverse-osmosis system without batteries*. Desalination 153, pp. 1-8.

Thomson M., Miranda M.S., Infield D. (2002b). *A small-scale seawater reverse-osmosis system with excellent energy efficiency over a wide operating range*. Desalination 153, pp. 229-236.

United Nations Development Report UNDP (1998), Human Development Report 1998, Goetzky, Bonn, Germany.

Weiner D., Fisher D., Moses E.J., Katz B. and Meron G. (2001), *Operation experience of a solar- and wind-powered desalination demonstration plant*, Desalination 137, pp. 7-13.

World Health Organisation WHO (1993), *Guidelines for Drinking Water Quality. Vol. 1: Recommendations*, World Health Organisation, Geneva, Switzerland.